SM358

Physics Toolkit

This toolkit consists of a glossary of physics terms.

Italicized words are cross-references to other entries in this Glossary.

absolute temperature A temperature measured on the *absolute temperature scale*.

absolute temperature scale The *SI* scale of temperature measured in *kelvin* (K). On this scale, the lowest conceivable temperature, *absolute zero*, is 0 K.

absolute zero The lowest conceivable temperature for any *system*. It is represented by the value 0 K on the *absolute temperature scale*, and corresponds to a temperature of $-273.15\,^\circ\mathrm{C}$ on the Celsius temperature scale. In *classical physics*, where temperature is a measure of molecular agitation, absolute zero corresponds to all *particles* being in a state of rest with a minimum mutual *potential energy*.

acceleration The acceleration of a *particle* is the instantaneous rate of change of its *velocity*. In general, acceleration is represented by an *acceleration vector*

$$\mathbf{a} = \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2}.$$

where $\mathbf{v}$ is the particle's *velocity vector* and $\mathbf{r}$ is its *position vector*.

For motion confined to one dimension (the x-axis) acceleration can be represented by a single *scalar* quantity, $a_x = \mathrm{d}v_x/\mathrm{d}t = \mathrm{d}^2x/\mathrm{d}t^2$.

acceleration vector A *vector* that defines the *acceleration* of a *particle*. If the particle is changing its direction of motion, the acceleration vector will not be in the same direction as the *velocity vector*.

alpha decay A form of *radioactive decay* in which the *nucleus* of an *atom* ejects an energetic *alpha particle*. As a result, the *atomic number* Z of the emitting nucleus is reduced by two, and its *mass number* A is reduced by four.

alpha particle A type of composite *particle*, consisting of two *protons* and two *neutrons* bound together. An alpha particle is identical to the *nucleus* of a *helium atom* with *mass number* 4, and is therefore the same as a doubly-*ionized* helium-4 atom. The term is generally used in the context of alpha-particle emission from certain unstable nuclei in the *radioactive decay* process known as *alpha decay*.

ampere The *SI* unit of *electric current*, represented by the symbol A. It is defined in such a way that, if a steady current of one ampere flows in each of two straight parallel infinitely-long wires, of negligible cross section, set one metre apart in a vacuum, the *magnitude* of the *magnetic force* experienced by each wire is 2×10^{-7} N per metre of its length. The ampere is colloquially called the amp.

amplitude The *magnitude* of the maximum deviation of an *oscillation* or *wave* from equilibrium. For a *sinusoidal* oscillation described by the function $x(t) = A\cos(\omega t + \phi)$, the positive constant A is the amplitude of the oscillation. For a sinusoidal wave described by the function $u(x,t) = A\cos(kx - \omega t + \phi)$, the positive constant A is the amplitude of the wave.

angular frequency The rate of change of the *phase* of an *oscillation* or *wave*. The angular frequency ω is given by

$$\omega = 2\pi f = \frac{2\pi}{T},$$

where f is the *frequency* and T is the *period* of the oscillation or wave. The *SI* unit of angular frequency is the inverse second, s^{-1}. (Some authors use rad s^{-1}, but this clashes with the fact that product of angular frequency and time appears in functions such as $\sin(\omega t)$ and, in this context, ωt must be a pure number to ensure that an expansion of the sine function gives a power series in which different terms have the same units.)

angular momentum A quantity that describes a state of *rotational motion*. In *classical physics*, the angular momentum of *particle* about an origin O is defined by the *vector product*

$$\mathbf{L} = \mathbf{r} \times \mathbf{p},$$

where $\mathbf{r}$ is the *displacement* of the particle from O and $\mathbf{p}$ is the *momentum* of the particle. The *SI* unit of angular momentum is $\mathrm{kg\,m^2\,s^{-1}}$.

A classical rigid body rotating about a fixed axis has a *component* of angular momentum along the axis of *magnitude*

$$L = I\omega,$$

where I is the *moment of inertia* of the body about the fixed axis of rotation and ω is the angular speed of the body about this axis. If the axis of rotation is an axis of symmetry (or a so-called principal axis), there are no components of angular momentum perpendicular to the axis of rotation, and the magnitude of the angular momentum is $I\omega$. (This is the only case of rigid body rotation considered in this module).

anode The *electrode* through which an *electric current* flows into a device; if the current is carried by *electrons*, it is the electrode through which electrons leave the device. In a battery, the anode is the negative contact, through which electrons leave the battery. In a vacuum electronic device (such as a *cathode ray tube*), the anode is given a positive *charge* by external means; it therefore draws negatively-charged electrons from the partially-evacuated chamber. Compare with *cathode*.

antineutrino The *antiparticle* of a *neutrino*.

antiparticle All *elementary particles* with *mass*, stable and unstable, have antiparticles. An antiparticle has exactly the same mass as the corresponding particle, but it has the opposite signs for other attributes, such as *electric charge*. When a particle collides with its own antiparticle, the two may annihilate each other completely, producing *electromagnetic radiation* (usually *gamma rays*).

antiproton The negatively-charged *antiparticle* of the *proton*.

atom The smallest electrically-neutral sample of an *element* that retains the fundamental chemical and physical identity of that element. An atom consists of a positively-charged *nucleus* surrounded by a cloud of negatively-charged *electrons*. Most of the *mass* of an atom is contained in its nucleus, but atomic sizes are generally determined by the distribution of electrons. Atomic radii vary from about 5×10^{-11} m to 3×10^{-10} m.

atomic number The number of *protons* in the *nucleus* of a particular type of *atom*, and hence the number of *electrons* in the neutral atom. An *element* is identified by its atomic number Z, which determines its chemical properties. The atomic number is usually denoted by the symbol Z; *hydrogen*, *helium* and lithium atoms have $Z = 1$, 2 and 3 respectively.

beta decay A form of *radioactive decay* in which the *atomic number* Z of the original *nucleus* changes by ± 1 and the *mass number* remains unchanged. There are three distinct types of beta decay. In negative beta decay (β^--decay) a *neutron* is replaced by a *proton* and the nucleus emits an *electron* and an *antineutrino*. In positive beta decay (β^+-decay) a proton is replaced by a neutron and the nucleus emits a *positron* and a *neutrino*. In *electron capture* a proton is replaced by a neutron when the nucleus captures an electron in low-lying atomic *energy level* and emits a neutrino; an *X-ray* is emitted as an electron in a higher atomic energy level falls into the vacancy left as a result of the capture.

binding energy The minimum *energy* needed to separate a *system* into separate *particles*.

black body A hypothetical ideal absorber of *electromagnetic radiation* that absorbs all the radiation that is incident upon it. Such a body is also an ideal emitter and emits electromagnetic radiation with a *spectrum* that depends only on the temperature of the body. A black body is closely approximated by a small transparent window into the cavity of an oven with strongly-absorbing walls.

Bohr model A semi-quantum model of *atoms* introduced by Niels Bohr in 1913. The model assumes that a central, positively-charged, *nucleus* is orbited by one or more *electrons* that are held in place by *electrostatic forces* given by *Coulomb's law*. It takes the radical step of assuming that only certain stable orbits are possible. Each *Bohr orbit* is characterized by a quantum number n and an *orbital angular momentum* of *magnitude* $n\hbar$, where $n = 1, 2, 3, \ldots$ is a positive integer and $\hbar$ is *Planck's constant* divided by 2π. The model further assumes that electrons do not emit *electromagnetic radiation* as long as they remain in one of the allowed orbits, but that emission (or absorption) of electromagnetic radiation occurs when an electron makes a transition from one orbit to another.

Bohr orbit A stable orbit for an *electron* in the *Bohr model* of an *atom*. For a *hydrogen atom*, a Bohr orbit with quantum number n is a circle of radius $r_n = n^2 a_0$, where a_0 is the *Bohr radius*. An electron in this orbit has an *orbital angular momentum* of *magnitude* $L = n\hbar$ and a *speed* $v_n = e^2/4\pi\varepsilon_0\hbar n$ where e is the magnitude of the electron's *charge*, ε_0 is the *permittivity of free space* and $\hbar$ is *Planck's constant* divided by 2π.

Bohr radius The radius of the lowest *Bohr orbit* in the *Bohr model* of the *hydrogen atom*. Its value is

$$a_0 = \frac{4\pi\varepsilon_0}{e^2}\frac{\hbar^2}{\mu} = 5.29\times 10^{-11}\,\text{m},$$

where e is the *magnitude* of the *charge* of an *electron*, ε_0 is the *permittivity of free space*, $\hbar$ is *Planck's constant* divided by 2π and μ is the *reduced mass* of the electron and *proton*.

Boltzmann's constant A physical constant k that relates *absolute temperature* to *energy*. In *SI* units, $k = 1.38\times 10^{-23}\,\text{J}\,\text{K}^{-1}$.

Cartesian coordinate system A set of three mutually perpendicular axes pointing outwards from a single origin. The axes are called the x-axis, the y-axis and the z-axis. Such a coordinate system is usually chosen to be right-handed so that, if the fingers of the right hand initially point in the x-direction, and are then bent to point in the y-direction, the outstretched right thumb points in the z-direction.

Cartesian coordinates Coordinates x, y and z that represent the position of a point relative to a given *Cartesian coordinate system*.

Cartesian unit vectors The three *unit vectors* $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ that point in the directions of the axes of a *Cartesian coordinate system*.

cathode The *electrode* through which an *electric current* flows out of a device; if the current is carried by *electrons*, it is the electrode through which electrons enter the device. In a battery, the cathode is the positive contact, through which electrons enter the battery. In a vacuum electronic device (such as a *cathode ray tube*), the cathode is given a negative *charge* by external means; it therefore liberates negatively-charged electrons into the partially-evacuated chamber. Compare with *anode*.

cathode ray tube A partially-evacuated tube in which *electrons* are liberated from a *cathode*, accelerated through a high *voltage* and allowed to strike a fluorescent screen.

centre of mass For an n-particle *system*, whose *particles* have *masses* $m_1, \ldots, m_n$ and *position vectors* $\mathbf{r}_1, \ldots, \mathbf{r}_n$ relative to an origin O, the centre of mass has position vector

$$\mathbf{r}_{\text{cm}} = \frac{m_1\mathbf{r}_1 + \ldots + m_n\mathbf{r}_n}{m_1 + \ldots + m_n} = \frac{\sum_{i=1}^{n} m_i\mathbf{r}_i}{M}$$

where $M = \sum_{i=1}^{n} m_i$ is the total mass of the system.

If the total *external force* acting on the system is $\mathbf{F}$, the *acceleration* of the centre of mass is $\mathbf{a} = \mathbf{F}/M$. The centre of mass can therefore be regarded as the point at which *Newton's laws* for particle motion can most easily be applied to a system. If the system experiences no net external force (e.g. is isolated), its centre of mass moves with constant *velocity*.

centre-of-mass frame A *frame of reference* whose origin permanently coincides with the *centre of mass* of a given *system* of *particles*.

charge Often used as an abbreviation for *electric charge*.

chemical element A specific type of *atom*, characterized by a particular *atomic number* Z. The *nucleus* of the atom contains Z *protons*, and a neutral atom contains Z *electrons*. Different *isotopes* of an element have different atomic *masses* because of different numbers of *neutrons* in their nuclei, but all isotopes of the same element have the same chemical properties.

classical physics A term given to branches of physics that do not rely on quantum ideas. Classical physics embraces classical mechanics and subjects such as classical electromagnetism, fluid mechanics and thermodynamics. Most physicists regard special and general relativity as belonging to classical physics, which implies that the major revolution of twentieth-century physics was quantum physics, not relativity.

coherent waves Two *waves* are said to be coherent with one another if knowledge of the *phase* of one wave at a particular position and time enables the phase of the other wave to be predicted at some other position and time.

component The component of a *vector* along a given axis is the *magnitude* of the vector times the cosine of the angle between the direction of the vector and the direction the axis. Components can be positive, negative or zero.

Compton effect The phenomenon in which a *photon* scatters from an *electron* and transfers some of its *energy* to the electron. The loss in photon energy is accompanied by an increase in *wavelength* of the scattered *electromagnetic radiation*, with larger scattering angles corresponding to larger wavelength shifts.

The Compton effect was historically important in establishing that photons behave like *particles*, exchanging energy and *momentum* when they collide with electrons. Relativistic energy and relativistic momentum are conserved in each collision.

conservation of angular momentum The principle that, if a *system* experiences no net external *torque* about a given point, then its total *angular momentum* about that point remains constant.

conservation of energy The principle that the total *energy* of any *isolated system* remains constant in time. In applying this principle, it is essential to include the energies of any *photons* that are absorbed or emitted.

conservation of linear momentum Another term for *conservation of momentum*.

conservation of momentum The principle that, if the total *external force* on a *system* is zero, the total *momentum* of the system remains constant. Sometimes called the *conservation of linear momentum*.

conservative force A *force* with the characteristic that the *work* it does when its point of application moves from one point to another is independent of the route followed between those two points. This is equivalent to the requirement that the work done by the force when its point of application moves around a closed loop is equal to zero. In one dimension, a force is conservative if it depends on position only, so that the force has the form $F_x(x)$. In this case, we can define a *potential energy function* $V(x)$, which is related to the force by

$$V(x) = -\int F_x(x)\,\mathrm{d}x + \text{constant}$$

or equivalently,

$$F_x(x) = -\frac{\mathrm{d}V}{\mathrm{d}x}.$$

constructive interference The phenomenon in which two or more *waves* reinforce one another when they are superimposed at a given point. Contrast with *destructive interference*.

Cooper pair A bound pair of *electrons* in which the two electrons propagate in opposite directions and (normally) have opposite *spin* states. Cooper pairs are formed in a *superconductor* at low temperatures.

coulomb The *SI* unit of *electric charge*, represented by the symbol C. A coulomb is the charge transferred by a *current* of one *ampere* flowing for one second. Thus, $1\,\mathrm{C} = 1\,\mathrm{A\,s}$.

Coulomb force The *electrostatic force* between two charged *particles*, given by *Coulomb's law*.

Coulomb potential energy function A function specifying the mutual *potential energy* of two charged *particles* in a vacuum. This is given by

$$E_{\text{pot}} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r},$$

where q_1 and q_2 are the *charges* of the particles, r is their separation and ε_0 is the *permittivity of free space*. By convention, the *zero of potential energy* is taken to correspond to infinite separation of the particles, so the Coulomb potential energy of oppositely-charged particles is negative.

Coulomb's law The physical law quantifying the *electrostatic force* between two stationary charged *particles*. This *force* acts along the line joining the particles; it is repulsive if the *charges* have the same sign and attractive if they have opposite signs. The force has *magnitude*

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2},$$

where q_1 and q_2 are the charges of the particles, r is the distance between them and ε_0 is the *permittivity of free space*.

current An abbreviation for *electric current*.

cycle The shortest part of an *oscillation* or *wave* over which the motion repeats itself; a cycle endures for exactly one *period*.

decay See *radioactive decay* or *particle decay*.

density The *mass* per unit volume in the immediate vicinity of a given point.

dependent variable In a function $f(x, y, \ldots, z)$, the dependent variable is f. Contrast with the *independent variables* $x, y, \ldots, z$.

destructive interference The phenomenon in which two or more *waves* cancel one another when they are superimposed at a given point. Contrast with *constructive interference*.

deuterium atom An *isotope* of *hydrogen* with *mass number* $A = 2$. A neutral deuterium atom has a single *electron* outside a deuterium *nucleus*, which consists of a bound state of a *proton* and a *neutron* (a *deuteron*).

deuteron A bound state of a *proton* and a *neutron*. A deuteron is the *nucleus* of a *deuterium atom*.

diatomic molecule A *molecule* consisting of two *atoms* bound together.

diffraction The spreading of a *wave* that occurs when it passes through an aperture or around an obstacle. Diffraction is caused by the *interference* of waves taking different routes. Classical examples include the diffraction of water waves, sound waves and *light* waves.

diffraction pattern The *intensity* pattern of a *wave* that has been diffracted after passing through an aperture or around an obstacle. The *diffraction* arises as a result of *interference*, so the diffraction pattern generally displays *interference maxima* and *interference minima*.

displacement The change in position in going from the one point to another. The *magnitude* of the displacement is equal to the distance between the two points. The direction of the displacement is the direction of the line from the first point to the second. If a *particle* moves in two- or three-dimensional space, its displacement is represented by a *displacement vector*.

displacement vector A *vector* quantity representing the *displacement* between two points.

electric charge A fundamental property of *matter* that determines the *electric* and *magnetic forces* between *particles*. There are two types of charge: positive and negative. *Protons* are positively charged (with charge e) and *electrons* are negatively charged (with charge $-e$). The *SI* unit of charge is the *coulomb* (C) and $e = 1.60 \times 10^{-19}\,\mathrm{C}$.

electric current The electric current along a wire is the rate of flow of *electric charge* through a fixed plane perpendicular to the axis of the wire. If the current is carried by *electrons* (which are negatively-charged), it is in the opposite direction to the direction of flow of electrons.

electric field A *vector field* that determines the *electric force* on a charged *particle* placed at any given point. The electric field at point P is the electric force per unit *charge* experienced by a small test charge placed at P. The *SI* unit of electric field is $\mathrm{N\,C^{-1}}$.

electric force The *force* experienced by a charged *particle* due to an *electric field*, given by

$$\mathbf{F} = q\boldsymbol{\mathcal{E}},$$

where q is the *charge* of the particle and $\boldsymbol{\mathcal{E}}$ is the electric field at the position of the particle.

electrical conductivity A measure of the ease with which a material conducts an *electric current*. If a homogeneous slab of material of length l and cross-sectional area A has a *potential difference* V maintained across its ends, the current flowing through the slab has *magnitude*

$$i = \frac{\sigma A V}{l},$$

where σ is the electrical conductivity of the material. A wire of length l and cross-sectional area A has electrical resistance $R = l/A\sigma$. The *SI* unit of electrical conductivity is $\mathrm{ohm^{-1}metre^{-1}} = \Omega^{-1}\,\mathrm{m^{-1}}$.

electrical resistivity The reciprocal of *electrical conductivity*.

electrode A conducting plate at which charged *particles* (usually *electrons*) are collected or emitted in a cell, battery, vacuum electronic device, etc. The *electric current* enters the device via the *anode* and leaves it via the *cathode*. Mnemonic: ACID (Anode Current Into Device).

electromagnetic radiation Self-sustaining electromagnetic disturbances that propagate through space with *electric* and *magnetic fields* decreasing no faster than $1/\text{distance}$, and the corresponding energy density decreasing no faster than $1/\text{distance}^2$. Realized through *electromagnetic waves*.

electromagnetic wave A *transverse wave* in which an *electric field* and a *magnetic field* oscillate *in phase* with one another. The simplest type of electromagnetic wave is a *monochromatic plane wave* in a homogeneous medium; such a wave is *sinusoidal*, with a constant values of *frequency* f, *wavelength* λ and *speed* $f\lambda$. In a vacuum, the speed of all electromagnetic waves is a universal constant, the *speed of light* c. See also *electromagnetic radiation*.

Electromagnetic waves range from *gamma rays* at short *wavelengths* through *X-rays*, *ultraviolet radiation*, *visible light*, *infrared radiation* and *microwaves* to *radio waves* at long wavelengths.

electron A negatively-charged *particle*, currently regarded as structureless, with about one two-thousandth the *mass* of a *proton*. Electrons are the carriers of *electric current* in metallic conductors.

electron capture See *beta decay*.

electronvolt A unit of *energy* defined as the *magnitude* of the energy gained when an *electron* is accelerated through a *potential difference* of one *volt*. An electronvolt is given the symbol eV, and is equal to $1.60 \times 10^{-19}\,\mathrm{J}$.

According to the conventional rules for *SI* prefixes, $1\,\mathrm{meV} = 10^{-3}\,\mathrm{eV}$, $1\,\mathrm{keV} = 10^{3}\,\mathrm{eV}$, $1\,\mathrm{MeV} = 10^{6}\,\mathrm{eV}$ and $1\,\mathrm{GeV} = 10^{9}\,\mathrm{eV}$. The units meV, eV, MeV and GeV are convenient for discussing molecular rotations, electronic transitions, nuclear physics and *elementary particle* physics, respectively.

electrostatic force The *force* between stationary charged *particles*. For two particles in a vacuum, this force is given by *Coulomb's law*.

electrostatic potential The electrostatic potential at a given point, due to a given arrangement of stationary *electric charges*. is the *electrostatic potential energy* per unit charge of a charged *particle* placed at the given point.

electrostatic potential energy *Potential energy* due to *electrostatic forces*. For two *particles* in a vacuum, the electrostatic potential energy is given by the *Coulomb potential energy function*. Do not confuse with *electrostatic potential*.

element (i) An abbreviation for chemical element. Traditionally, an element is a substance that cannot be divided by chemical means, heating or the passage of an *electric current*. More precisely, a sample of any given element consists of *matter* entirely composed of *atoms* with the same *atomic number*, and hence the same number of *protons* in their *nuclei*.

(ii) In mathematics, an element is a basic part of something (e.g. a volume element).

elementary particle A piece of *matter* that is smaller than a *nucleus*. Such *particles* include *protons* and *neutrons*, as well as *electrons* and *quarks*. They may or may not be truly fundamental constituents of matter.

energy In *classical physics*, energy is the property of a *system* that measures its capacity for doing *work* on a body, or for changing the *kinetic energy* of a *free particle*. Energy is a *scalar* quantity that is conserved in any *isolated system*. The *SI* unit of energy is the *joule*, represented by the symbol J, where $1\,\mathrm{J} = 1\,\mathrm{N\,m} = 1\,\mathrm{kg\,m^2\,s^{-2}}$.

energy level An *energy* that characterizes a particular quantum state of a *system*.

event An ideal physical occurrence that occupies a point in space and occurs at an instant in time. Processes occurring in a small region of space, during a brief interval of time, can be modelled as events.

excited state A quantum state of a given *system* with an *energy* that is greater than the *ground-state* energy of the system.

external force A *force* acting on a *system*, caused by agencies outside the system.

field A quantity which, at any given instant, has definite values throughout a continuous region of space. Common fields involve *scalar* or *vector* quantities. Examples include pressure fields, gravitational fields, *electric fields* and *magnetic fields*. Many fields determine the *forces* acting on *particles*, but this need not be so (e.g. a temperature field).

force Informally, the amount of 'push' or 'pull' exerted on a *particle* which, if unopposed, causes it to depart from the *uniform motion* predicted by *Newton's first law*. Force therefore quantifies the influence that causes (or tends to cause) *acceleration*. If a particle of *mass* m has acceleration $\mathbf{a}$ relative to an *inertial frame of reference*, the total force acting on the particle is

$$\mathbf{F} = m\mathbf{a},$$

which is *Newton's second law*. The *SI* unit of force is the *newton*, represented by the symbol N, where $1\,\mathrm{N} = 1\,\mathrm{kg\,m\,s^{-2}}$.

force constant The positive constant C that appears in *Hooke's law*, $F_x = -Cx$, and in the expression for the *potential energy function* of a *simple harmonic oscillator*, $V(x) = \frac{1}{2}Cx^2$. The *SI* unit of a force constant is $\mathrm{N\,m^{-1}}$.

frame of reference A set of coordinate axes and synchronized clocks, which makes it possible to specify uniquely the location in space and time of any given *event*.

free particle A *particle* that is subject to no *forces*, and for which the *potential energy* is a constant independent of position (usually set equal to zero).

frequency The number of *cycles* per unit time of an *oscillation* or *wave*. The frequency f is related to the *period* T by $f = 1/T$. The *SI* unit of frequency is the *hertz* ($1\,\mathrm{Hz} = 1\,\mathrm{s^{-1}}$). Compare with *angular frequency*.

fusion An abbreviation for *nuclear fusion*.

gamma rays *Electromagnetic radiation* with a *wavelength* shorter than 10^{-11} m, or equivalently a *frequency* greater than about 3×10^{19} Hz. A common source of gamma rays is *nuclei* which undergo *radioactive decay*.

Geiger counter A device for detecting *particles* that are able to cause the *ionization* of *molecules* in a gas. Also called a Geiger–Müller tube.

gluon Any member of the family of eight *elementary particles* with *spin*-1 that are currently believed to be responsible for mediating the *strong interaction*.

harmonic motion Another term for *simple harmonic motion*.

helium atom An *atom* with *atomic number* $Z = 2$, and therefore with two *protons* in its *nucleus*, and two *electrons* outside the nucleus. A helium-4 atom has two *neutrons* in its nucleus (an *alpha particle*) while the rarer *isotope* helium-3 has only one neutron in its nucleus.

hertz The *SI* unit of *frequency*, represented by the symbol Hz. A frequency of 1 Hz is equivalent to one *cycle* per second, so $1\,\mathrm{Hz} = 1\,\mathrm{s^{-1}}$.

Hooke's law The *force* on a *particle* is said to obey Hooke's law if it is a *restoring force* (always acting towards the equilibrium position) and is proportional to the *displacement* of the particle from equilibrium. In one dimension, we write

$$F_x = -Cx,$$

where x is the displacement from the equilibrium position, and the proportionality constant C is called the *force constant*. In *classical physics*, such a force leads to *simple harmonic motion*.

hydrogen atom An *atom* with *atomic number* $Z = 1$ and therefore with one *proton* in its *nucleus* and a single *electron* outside the nucleus. Different *isotopes* of hydrogen have no *neutrons*, one neutron (*deuterium*) or two neutrons (tritium). Hydrogen *molecules* consist of two hydrogen atoms bound together.

in phase Two *oscillations* or *waves* are said to be in phase with one another if they permanently have the same *phase*.

independent variable In a function $f(x, y, \ldots, z)$, the independent variables are $x, y, \ldots, z$. Contrast with the *dependent variable* f.

inertial frame of reference A *frame of reference* set up and moving in such a way that all *free particles* have zero *acceleration*, in accordance with *Newton's first law*. The laws of physics (including those of classical mechanics and quantum mechanics) are

normally expressed in terms of observations made in inertial frames of reference.

infrared radiation *Electromagnetic radiation* with a *wavelength* between about 7×10^{-7} m and 1×10^{-3} m, or equivalently a *frequency* between about 4×10^{14} Hz and 3×10^{11} Hz.

intensity of a wave For a classical *wave*, intensity is the amount of *energy* transported by the wave per unit time per unit area perpendicular to the direction of wave propagation. Intensity is proportional to the square of the *amplitude* of the wave. If a point source of waves radiates energy equally in all directions, the intensity of the waves is inversely proportional to the square of the distance from the source. The *SI* unit of intensity is *watt* per square metre ($\mathrm{W\,m^{-2}}$).

interference A phenomenon arising from the *superposition* of two or more *coherent waves*, resulting in a pattern of *interference maxima* and *interference minima*. See also *constructive interference* and *destructive interference*.

interference maxima Features of *interference patterns* produced when two or more *coherent waves* interfere with one another. Interference maxima occur at points where the contributing waves reinforce one another, leading to a local maximum in the *intensity* of the wave (*constructive interference*).

interference minima Features of *interference patterns* produced when two or more *coherent waves* interfere with one another. Interference minima occur at points where the contributing waves cancel one another, leading to a local minimum in the *intensity* of the wave (*destructive interference*).

interference pattern A pattern of peaks and troughs in *intensity* that occurs when *coherent waves* from a spatially extended source (or more than one source) are allowed to interfere with one another. See *interference*.

ion An electrically-charged *atom* formed when a neutral atom loses or gains one or more *electrons* so that the *magnitude* of its total electronic *charge* is not equal to the magnitude of the charge of the *nucleus*.

ionic crystal A crystal composed mainly of positive and negative *ions* held together by attractive *electrostatic forces* between ions of opposite sign. A familiar example is the crystal of common salt, NaCl.

ionization The process in which a neutral *atom* loses one or more *electrons* to produce a positive *ion* and one or more unbound electrons.

isolated system A *system* that is free from external influences. Such a system is not acted upon by *external forces* and exchanges no *energy* or *matter* with the rest of the Universe.

isotope Isotopes of a given *element* are *atoms* or *nuclei* with the same number of *protons*, and therefore the same *atomic number*, Z. Different isotopes have different numbers of *neutrons*, and therefore different *mass numbers*, A.

The usual symbol for an isotope is $^{A}\mathrm{Sy}$, where Sy is the chemical symbol for the element. Since Sy determines Z, the fuller notation $^{A}_{Z}\mathrm{Sy}$ is strictly redundant, but may be helpful for elements for which Z is not widely-remembered. For example, the isotope of silicon with $A = 27$ and $Z = 14$ can be written as $^{27}\mathrm{Si}$ or $^{27}_{14}\mathrm{Si}$. Less formally, this isotope is referred to as silicon-27.

joule The *SI* unit of *energy*, represented by the symbol J. One joule is the *work* done on a body by a *force* of *magnitude* one *newton* when the body moves one metre in the direction of the force. So $1\,\mathrm{J} = 1\,\mathrm{N\,m} = 1\,\mathrm{kg\,m^2\,s^{-2}}$.

kelvin The unit of temperature on the *absolute temperature scale*, represented by the symbol K. This is the *SI* unit of temperature. A temperature difference of one kelvin ($1\,\mathrm{K}$) is equivalent to a temperature difference of one degree Celsius ($1\,^{\circ}\mathrm{C}$), but the two scales have different zeros, with zero kelvin corresponding to *absolute zero*, the lowest conceivable temperature for a *system* in equilibrium.

kinetic energy *Energy* due to motion. The kinetic energy of a *particle* is given by

$$E_{\mathrm{kin}} = \frac{1}{2}mv^2 = \frac{p^2}{2m},$$

where m is the *mass* of the particle, v is its *speed* and p is the *magnitude* of its *momentum*.

laser A device which when stimulated with incident *electromagnetic radiation* produces an intense source of *coherent light* in the form of a narrow beam. The word ‘laser’ is an acronym for Light Amplification by the Stimulated Emission of Radiation.

lepton One of the major families of *elementary particles*, consisting of six particles and their *antiparticles*. Leptons are currently believed to be truly fundamental particles. They participate in the *weak interaction*, but not in the *strong interaction*.

Leptons are classified into three generations: (i) *electron* and electron *neutrino*; (ii) *muon* and muon neutrino; (iii) tauon and tauon neutrino and their corresponding antiparticles.

light A term normally reserved for *visible light*, but sometimes used for any type of *electromagnetic radiation*.

linear combination Given a set of functions $f_1(x)$, $f_2(x)$, ..., and a set of (possibly *complex*) constants c_1, c_2, ..., any expression of the form

$$c_1 f_1(x) + c_2 f_2(x) + \ldots$$

is called a linear combination of $f_1(x)$, $f_2(x)$, ...

Also called linear superposition.

linear momentum An alternative term for *momentum*.

longitudinal wave A *wave* composed of *oscillations* that take place in a direction parallel to the direction of propagation of the wave. Contrast with *transverse wave*.

magnetic field A *vector field* which determines the *magnetic force* on a charged *particle* moving through a given point. The magnetic field at a point P is a vector quantity $\mathbf{B}$ such that the magnetic force on a particle of *charge* q, passing through P with *velocity* $\mathbf{v}$, is given by the *vector product*

$$\mathbf{F} = q\big(\mathbf{v} \times \mathbf{B}\big).$$

magnetic force A velocity-dependent *force* experienced by a *particle* with an *electric charge* moving in a *magnetic field*. The force is perpendicular to both the *velocity* of the particle and the magnetic field, and is given by the *vector product*

$$\mathbf{F} = q\big(\mathbf{v} \times \mathbf{B}\big),$$

where q is the particle's *charge*, $\mathbf{v}$ is its velocity and $\mathbf{B}$ is the magnetic field at the position of the particle.

magnitude A non-negative *real* quantity. The magnitude of a *scalar* Q is a non-negative quantity $|Q|$ describing the size of Q, irrespective of its sign. The magnitude of a *vector* $\mathbf{a}$ is a non-negative quantity $|\mathbf{a}|$, describing the size of $\mathbf{a}$, irrespective of its direction; this is usually written as a, omitting both the bold print and the modulus signs.

mass A quantity that represents the amount of *matter* in an object and is independent of the object's position in the Universe. Mass occurs in *Newton's second law*, where it describes the reluctance of a body to change from a state of uniform linear motion. The *SI* unit of mass is the kilogram (kg).

mass number The total number of *neutrons* and *protons* in a *nucleus*, $A = N + Z$, where N is the number of neutrons and Z is the number of protons (the *atomic number*).

matter A general term for material substances and *particles*, irrespective of their form.

meson A term used to describe any *elementary particle* that participates in the *strong interaction* and has zero or integer *spin*. Each meson is a combination of a *quark* and antiquark.

microwave *Electromagnetic radiation* with a *wavelength* between about 1×10^{-3} m and 1×10^{-1} m, or equivalently a *frequency* between about 3×10^{11} Hz and 3×10^{9} Hz.

molecule Traditionally, the smallest part of a pure substance that retains the chemical identity of that substance. From a microscopic point of view, a molecule is a particular group of *atoms* bound together in a particular way.

moment of inertia A quantity that represents the reluctance of a body to depart from a state of constant *angular momentum* along a given axis. For a fixed axis of rotation, the moment of inertia is defined by

$$I = \sum_i m_i d_i^2,$$

where the m_i is the *mass* of *particle* i, d_i is the distance of particle i from the axis of rotation, and the sum is over all the particles in the body.

momentum A *vector* quantity describing of the amount of *translational motion* of a *particle* or *system*. In classical mechanics, the momentum of a particle is

$$\mathbf{p} = m\mathbf{v},$$

where m is the particle's *mass* and $\mathbf{v}$ is its *velocity*. The momentum of a system of particles is the vector sum of the momenta of all the particles. The *SI* unit of momentum is $\mathrm{kg\,m\,s^{-1}}$. Also called *linear momentum*. Compare with *angular momentum*.

monochromatic wave A *wave* of a single *frequency*.

muon An *elementary particle* with the same *charge* as an *electron* and a *mass* that is 207 times greater than the mass of an electron. The muon has a half-life of 2.2×10^{-6} s and decays into an electron plus a *neutrino–antineutrino* pair.

neutrino A very weakly-interacting *lepton*. Neutrinos exist in three types: the electron neutrino, the muon neutrino and the tauon neutrino.

neutron An electrically-neutral *elementary particle* which is a constituent of all atomic *nuclei* (except the common form of *hydrogen*). A neutron has a *mass* slightly greater than that of a *proton*, it has no net *charge*, but it does have a magnetic dipole moment. The neutron is stable within an atomic nucleus, but is unstable in a vacuum where it has a half-life of 914 s.

neutron star A highly-compact stellar object composed of *matter* rich in *neutrons*. Neutron stars have a typical *density* of order $10^{15}\ \mathrm{kg\,m^{-3}}$ (about 10^{12} times the density of water). Measured neutron star *masses* are typically 1.4 times the mass of the Sun and their radii are thought to be about 8 to 10 km. Neutron stars are formed when massive stars collapse under their own gravitational attraction.

newton The *SI* unit of *force*, represented by the symbol N. A total force of *magnitude* 1 N will cause a *particle* of *mass* 1 kg to accelerate at $1\ \mathrm{m\,s^{-2}}$ in the direction of the force. So, $1\ \mathrm{N} = 1\ \mathrm{kg\,m\,s^{-2}}$.

Newtonian mechanics A branch of physics which attempts to explain the motion of objects in terms of the *forces* acting on them. It is based on *Newton's laws* and incorporates other important principles, such as the law of *conservation of energy*.

Newton's first law A physical law stating that a body will remain at rest or in a state of *uniform motion* unless it is acted on by an unbalanced *force*.

Newton's laws A set of three physical laws: *Newton's first law*, *Newton's second law* and *Newton's third law*.

Newton's second law A physical law stating that an unbalanced *force* acting on a body of finite fixed *mass* will cause that body to accelerate in the direction of the force and that the force $\mathbf{F}$ is equal to the product of the mass m and the *acceleration* $\mathbf{a}$, namely

$$\mathbf{F} = m\mathbf{a}.$$

For a *system* of *particles*, or an extended body, the law implies that the total *external force* is equal to the total mass times the acceleration of the *centre of mass*. Newton's second law may also be expressed in terms of *momentum* $\mathbf{p}$ as follows. The total force acting on a particle is equal to the rate of change of the particle's momentum:

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}.$$

For a system of particles or an extended body this implies that the total external force is equal to the rate of change of the total momentum.

Newton's third law A physical law stating that if body A exerts a *force* on body B, then body B exerts a force on body A, and that these two forces are equal in *magnitude* but act in opposite directions. So

$$\mathbf{F}_{\mathrm{AB}} = -\mathbf{F}_{\mathrm{BA}}$$

where $\mathbf{F}_{\mathrm{AB}}$ is the force on A due to B, and $\mathbf{F}_{\mathrm{BA}}$ is the force on B due to A.

nodes Fixed points of zero disturbance in a *standing wave* (excluding points on the boundaries of the region where the disturbance takes place).

nuclear fusion A process in which two *nuclei* fuse together to form a larger nucleus. If the final nucleus has *mass number* $A \leq 56$ or thereabouts (e.g. ^{56}Fe), the *mass* of the final nucleus is less than the sum of the masses of the initial nuclei, and *energy* is released.

In stars, fusion is crucial for energy release and for the conversion of primordial *hydrogen* into other light *elements*, from *helium* up to iron. Fusion reactions are also the basis for the energy released in hydrogen bombs.

nuclei The plural of *nucleus*.

nucleus The positively-charged, very compact central part of an *atom*, composed of *protons* and *neutrons*. The nucleus is some 10^4 times smaller in radius than an atom, but contains nearly all the *mass*. The number of positively-charged protons in the nucleus of a given *element* is equal to the *atomic number*, Z.

nuclide A species of atomic *nucleus* that is characterized by the number of *protons* and *neutrons* that it contains. Another term for an *isotope*.

number density The number of specified entities (e.g. *atoms*) per unit volume.

orbital angular momentum *Angular momentum* associated with the motion of a *particle*, or a *system* of particles, through space. This includes the angular momentum associated with a rigid body that is rotating about a fixed axis, and all the other usages of angular momentum in *classical physics*. It does not include the quantum-mechanical concept of *spin angular momentum*.

oscillation A to-and fro motion, also called a *vibration*.

particle (i) In the context of *classical physics*, a particle is an idealized object that is thought of as existing at a single point in space. It has no size, shape or internal motion though it may have intrinsic properties such as *mass* and *charge*, as well as position, *velocity* and *acceleration*.

(ii) In the context of high-energy physics, a particle is a piece of *matter* that is of sub-nuclear size (an *elementary particle*). Such particles include *protons*, *neutrons* and *electrons*, and may or may not be truly fundamental constituents of matter.

particle decay A general process whereby an unstable *elementary particle* can spontaneously change into two or more other elementary particles.

period The time T taken for one complete *cycle* of an *oscillation* or *wave*; the reciprocal of the *frequency*: $T = 1/f$.

permittivity of free space The fundamental constant ε_0 that appears in the proportionality factor $1/4\pi\varepsilon_0$ for *Coulomb's law* and hence determines the *magnitude* of the *electrostatic force* between two *electric charges* separated by a fixed distance in a vacuum. It also appears in the electrostatic *potential energy function* for two charges. In *SI* units, $\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F\,m^{-1}} = 8.85 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$, where F is the symbol for farad.

phase For a *sinusoidal oscillation* $x(t) = A\cos(\omega t + \phi)$, where A is positive, the phase is the argument of the cosine, i.e. $\omega t + \phi$.

For a sinusoidal *wave* $u(x,t) = A\cos(kx - \omega t + \phi)$, where A is positive, the phase is the argument of the cosine, i.e. $kx - \omega t + \phi$. Do not confuse the phase with the *phase constant*.

phase constant For a *sinusoidal oscillation* $x(t) = A\cos(\omega t + \phi)$, where A is positive, the phase constant is ϕ.

For a sinusoidal *wave* $u(x,t) = A\cos(kx - \omega t + \phi)$, where A is positive, the phase constant is ϕ. Do not confuse the phase constant with the *phase*.

photoelectric effect The effect whereby *electrons* are emitted from *matter* (usually from a metallic *electrode*) when *electromagnetic radiation* of sufficiently high *frequency* is incident on it.

photon A packet of *electromagnetic radiation*. For radiation in a vacuum, with *frequency* f and *angular frequency* ω, each photon has *energy* $E = hf = \hbar\omega$ and *momentum* of *magnitude* $p = hf/c = \hbar\omega/c$, where h is *Planck's constant*, $\hbar$ is Planck's constant divided by 2π and c is the *speed of light* in a vacuum. Photons are emitted and absorbed in *radiative transitions* between *energy levels*.

Planck-Einstein formula The formula

$$E = hf$$

that relates the *energy* E of a *photon* of *electromagnetic radiation* to the *frequency* f of that radiation, where h is *Planck's constant*.

Planck's constant The fundamental constant $h = 6.63 \times 10^{-34}$ J s that appears in practically every equation of quantum mechanics, but never in those of *classical physics*. The quantity $h/2\pi$ is given the symbol $\hbar$.

Planck's constant was introduced in 1900 by Max Planck to explain the continuous *spectrum* of *electromagnetic radiation* emitted by *black bodies*.

plane-polarized wave See *polarization*.

plane wave A *wave* of constant *frequency* for which points of constant *phase* lie in planes perpendicular to the direction of propagation of the wave.

polarization The property of a *transverse wave* that implies the existence of a restriction on the direction of the transverse *oscillations*. For example, in a plane-polarized *wave*, the transverse oscillations occur in the same plane at all points on the path of the wave. In such cases the plane containing the direction of the oscillating variable and the direction of propagation of the wave is called the plane of polarization of the wave.

position vector A *vector* that defines the position of a *particle* in space.

positron A positively-charged *elementary particle*, the *antiparticle* of an *electron*.

potential A term often used for *electrostatic potential*. Do not confuse with *potential energy*.

potential difference A term used for the difference in *electrostatic potential* between two points. Do not confuse with a difference in *potential energy*.

potential energy *Energy* associated with the position of a *particle* or energy stored in a *system* by virtue of the positions of its component parts. In one dimension, a particle experiencing a *conservative force* $F_x(x)$ has the *potential energy function*

$$V(x) = -\int F_x(x)\,\mathrm{d}x + \text{constant}.$$

Equivalently,

$$F_x(x) = -\frac{\mathrm{d}V}{\mathrm{d}x}.$$

Any convenient point can be chosen to be the *zero of potential energy*.

potential energy function A function describing the *potential energy* of a *particle* or *system*.

proton An *elementary particle* which is a constituent of all atomic *nuclei*. The *mass* of a proton is slightly less that of a *neutron* and is almost 2000 times greater than that of an *electron*. The *charge* of a proton is positive and has the same *magnitude* as that of a negatively-charged electron.

quantum field theory The profound generalization of quantum mechanics that provides the framework for the full theory of atomic and subatomic *systems* with indefinite numbers of *particles*.

quark Any of the charged *elementary particles* that are currently believed to be fundamental constituents of *protons*, *neutrons*, pions and other sub-atomic particles (collectively known as hadrons). Six kinds of quark are currently known: up, down, charm, strange, top and bottom. Quarks are not expected to be observed as isolated particles.

All quarks have *spin*-$\frac{1}{2}$ and an *electric charge* that is a multiple of $\frac{1}{3}e$. A proton consists of three quarks, two with charge $+\frac{2}{3}e$ and one with charge $-\frac{1}{3}e$, plus *gluons* that bind them together. A neutron consists of three quarks, two with charge $-\frac{1}{3}e$ and one with charge $+\frac{2}{3}e$, plus gluons.

radiation A term used either as an abbreviation for *electromagnetic radiation* or when referring to *particles* emanating from a source (particularly those resulting from the *radioactive decay* of *nuclei*).

radiative transition A process in which a *system* (such as an *atom*) undergoes a transition from one quantum state to another by the emission or absorption of *electromagnetic radiation*. Such a process involves the creation or destruction of a *photon* (or, very rarely, more than one photon).

radio wave *Electromagnetic radiation* with a *wavelength* greater than around 10^{-1} m, or equivalently a *frequency* less than about 3×10^9 Hz.

radioactive decay A process in which an unstable *nucleus* loses *energy* by emitting ionizing *particles* and *electromagnetic radiation* and, as a result, transforms into a different type of nucleus.

radioactivity The phenomenon whereby an unstable *nucleus* spontaneously *decays* and, as a consequence, emits *particles* or *electromagnetic radiation*.

reduced mass A *mass* used to characterize a two-particle *system*. If the two *particles* have masses m_1 and m_2, the reduced mass of the two-particle system is

$$\mu = \frac{m_1 m_2}{m_1 + m_2}.$$

For two particles with positions $\mathbf{r}_1$ and $\mathbf{r}_2$, interacting via a mutual *potential energy function* $V(\mathbf{r}_2 - \mathbf{r}_1)$, the relative position $\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$ obeys the same equations as a single particle of mass μ in a potential energy well $V(\mathbf{r})$.

The reduced mass is always smaller than the mass of either of the particles in the system. In a *hydrogen atom*, μ is 0.9995 the mass of an *electron*, but for a *diatomic molecule* composed of two similar *atoms*, it is half the mass of either atom.

rest frame The *frame of reference* in which a given *particle* is at rest.

restoring force A *force* that acts in a direction which tends to restore a *particle* towards its equilibrium position.

right-hand rule A rule used to determine the direction of a *vector product* $\mathbf{a} \times \mathbf{b}$: point your right hand in the direction of the first *vector*, $\mathbf{a}$, and bend your fingers to point in the direction of the second vector, $\mathbf{b}$. The vector product $\mathbf{a} \times \mathbf{b}$ is perpendicular to both $\mathbf{a}$ and $\mathbf{b}$, in the direction of your outstretched right thumb.

rotational motion Motion in which all the *particles* of a *system* move at the same angular rate in circular paths, and the centres of all the circles are on a single line called the axis of rotation. Contrast with *translational motion*.

Rutherford model of the atom The atomic model put forward by Ernest Rutherford, in which the *electrons* in the *atom* are assumed to orbit outside a tiny core or *nucleus* which contains all the positive *charge* and almost all the *mass* of the atom.

scalar A quantity that is completely specified by a single number, or by a number times an appropriate unit of measurement. Contrast with *vector*.

selection rules Rules that govern whether particular *radiative transitions* are allowed or (to a first approximation at least) forbidden.

semiconducting material A material with an *electrical conductivity* intermediate between those of conductors and insulators. Examples include silicon and germanium.

SI An internationally agreed system of units of measurement. The system employs seven base units, including the kilogram (abbreviated to kg), the metre (abbreviated to m), the second (abbreviated to s), the *ampere* (abbreviated to A) and the *kelvin* (abbreviated to K). It also includes a number of derived units obtained by combining base units in various ways.

The SI system uses certain standard prefixes such as kilo $= 10^3$, mega $= 10^6$, giga $= 10^9$, tera $= 10^{12}$, milli $= 10^{-3}$, micro $= 10^{-6}$, nano $= 10^{-9}$ and pico $= 10^{-12}$. It also recognizes a number of standard symbols and abbreviations. SI itself is one of these symbols and stands for Système International.

simple harmonic motion In *classical physics*, a particular type of *oscillation* of a *particle* about a specified equilibrium position, characterized by the fact that the *acceleration* of the particle is always directed towards the equilibrium position and is proportional to the *displacement* from that point. In one dimension, simple harmonic motion may be described by a differential equation of the form

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \omega_0^2 x = 0,$$

which has the general solution

$$x(t) = A\cos(\omega_0 t + \phi),$$

where A is the *amplitude* of the motion, ω_0 is the *angular frequency* and ϕ is the *phase constant* of the motion.

simple harmonic oscillator In *classical physics*, a *particle* or *system* that performs *simple harmonic motion*.

sinusoidal Any function of the form

$$f(x) = A\sin(kx + \phi)$$

where A, k and ϕ are *real* constants, may be described as a sinusoidal function. Thus any *linear combination* of $\sin x$ and $\cos x$, with real coefficients, is a sinusoidal function.

solid state A term used to describe the field of physics in which the properties of solids are studied. It is also used to describe any electronic circuit or device containing solid-based *semiconducting materials* such as silicon or germanium.

spectra The plural of *spectrum*.

spectral lines Narrow lines (corresponding to narrow ranges of *frequency* or *wavelength*) seen in the *spectra* of substances and characteristic of those substances. Each spectral line results from a *radiative transition* and has a frequency $f = \Delta E/h$, where ΔE is the *magnitude* of the *energy* difference between the initial and final quantum states and h is *Planck's constant*.

spectrum Any particular distribution of *electromagnetic radiation*, expressed as a function of *intensity* versus *wavelength*, *frequency* or a related quantity such as *photon energy*. Many spectra consist of *spectral lines*, produced during *radiative transitions*

between discrete quantum states. Such a spectrum can provide an identifiable 'fingerprint' of a substance. .

speed The *magnitude* of *velocity*.

speed of light The *speed* of an *electromagnetic wave*. In an *inertial frame of reference*, in a vacuum, this is a universal constant $c = 3.00 \times 10^8\ \mathrm{m\,s^{-1}}$, independent of *amplitude*, *frequency*, *wavelength* or motion of the source.

spin See *spin angular momentum*.

spin angular momentum A type of *angular momentum* possessed as an intrinsic property of by certain *particles*. Spin is characterized by the spin quantum number s. We colloquially say that a particle has spin-s if its spin quantum number is equal to s. *Electrons*, *protons*, *neutrons* and *quarks* have spin-$\frac{1}{2}$.

standing wave A *wave* that oscillates without travelling through space. All points in the disturbance that constitutes the wave oscillate *in phase* with the same *frequency* but with different *amplitudes*. The fixed points of zero disturbance are called the *nodes* of the wave (although end-points of the disturbance are not always counted as nodes). A standing wave can be regarded as the sum of two *travelling waves*, propagating in opposite directions.

A familiar example from *classical physics* is the standing wave on a string stretched between fixed endpoints at $x = 0$ and $x = L$. This can be represented by the function

$$u(x,t) = A\sin(kx)\cos(\omega t + \phi),$$

where ω is the *angular frequency* and k is the *wave number*. The possible standing waves are restricted by the requirement that the distance between the fixed ends of the string must be equal to a whole number of half-*wavelengths*, which implies that $kL = n\pi$, where n is an integer.

strong force See *strong interaction*.

strong interaction A very short-range attractive *force* (also called the *strong force* or the *strong nuclear force*), that acts between *protons* and *neutrons*. It does not act on *electrons* and is almost independent of *electric charge*. The strong interaction is responsible for holding the *nucleus* together, despite the mutual electrostatic repulsion of its constituent protons.

strong nuclear force See *strong interaction*.

superconductivity The phenomenon exhibited by a number of materials, whereby, at a sufficiently low temperature, the *electrical resistivity* becomes zero (i.e. the *electrical conductivity* becomes infinitely large) and *magnetic fields* are excluded.

superconductor See *superconductivity*.

superposition In the context of *waves*, the adding of two or more wave disturbances. More generally, given a set of n functions $\Psi_1, \Psi_2, \ldots \Psi_n$, any expression of the form

$$\Psi = c_1\Psi_1 + c_2\Psi_2 + \cdots c_n\Psi_n$$

where $c_1, c_2, \ldots c_n$ are (possibly *complex*) constants, is said to be a linear superposition of $\Psi_1, \Psi_2, \ldots \Psi_n$.

system The portion of the Universe chosen as the subject of a scientific investigation. See also *isolated system*.

thermal energy A term for the *energy* that a *system* has by virtue of its temperature. In *classical physics*, this is a sum of the *kinetic energies* and the mutual *potential energy* of all basic *particles* (e.g. *molecules*) in the system, with the *zero of potential energy* set so that the thermal energy vanishes at the *absolute zero* of temperature.

The typical thermal energy of a molecule in a gas that is in thermal equilibrium at temperature T is approximately equal to kT, where k is *Boltzmann's constant*.

torque The torque of a *force* $\mathbf{F}$ about a fixed point O measures the turning effect of the force about the fixed point. It is given by the *vector product*

$$\boldsymbol{\Gamma} = \mathbf{r} \times \mathbf{F},$$

where $\mathbf{r}$ is the *displacement* of the point of action of the force from the fixed point O.

total (mechanical) energy The total (mechanical) energy of a *particle* is the sum of its *kinetic energy* and its *potential energy*.

trajectory The trajectory of a *particle* is the particle's path as it moves through space.

translational motion Motion in which every *particle* of a *system* moves with the same *velocity* in the same direction. Contrast with *rotational motion*.

transverse wave A *wave* composed of *oscillations* that take place in a direction perpendicular to the direction of propagation of the wave. Contrast with *longitudinal wave*.

travelling wave A *wave* that propagates from one place to another. A one-dimensional example of such a wave is represented by the function

$$u(x,t) = A\cos(kx - \omega t + \phi),$$

where the positive constant A is the *amplitude*, k is the *wave number*, ω is the *angular frequency* and ϕ is the *phase constant*. The quantity $kx - \omega t + \phi$ is the *phase* of the wave. Contrast with *standing wave*.

ultraviolet radiation *Electromagnetic radiation* with *wavelength* between about 1×10^{-8} m and 4×10^{-7} m, or equivalently with *frequency* between about 3×10^{16} Hz and 8×10^{14} Hz.

uniform motion A type of motion in which a *particle* travels with constant *velocity* in a straight line and does not accelerate.

unit vector A *vector* of unit *magnitude* in a given direction. A unit vector is dimensionless (it has no units).

vector A quantity with a definite *magnitude* and a definite direction in space. Vectors can be specified by giving their *components* in a given coordinate system.

vector product The vector product of two *vectors* $\mathbf{a}$ and $\mathbf{b}$ is a vector quantity defined by

$$\mathbf{a} \times \mathbf{b} = (a_y b_z - a_z b_y)\,\mathbf{e}_x + (a_z b_x - a_x b_z)\,\mathbf{e}_y + (a_x b_y - a_y b_x)\,\mathbf{e}_z,$$

where the *components* of the vectors are taken in a right-handed *Cartesian coordinate system* with *unit vectors* $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$. The vector product has *magnitude* $ab\sin\theta$, where θ is the angle between the directions of the vectors taken to be in the range $0 \leq \theta \leq \pi$. Its direction is given by the *right-hand rule*.

velocity The velocity of a *particle* is the instantaneous rate of change of its position. In general, velocity is represented by a *velocity vector*

$$\mathbf{v} = \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t},$$

where $\mathbf{r}$ is the *position vector* of the particle. For motion confined to one dimension (the x-axis), velocity can be represented by a single *scalar*, $v_x = \mathrm{d}x/\mathrm{d}t$. The *magnitude* of velocity is called *speed*.

velocity vector A *vector* that defines the *velocity* of a *particle*.

vibration A to-and-fro motion. See also *oscillation*.

vibrational motion A to-and-fro motion. See also *oscillation*.

visible light *Electromagnetic radiation* with *wavelength* between about 4×10^{-7} m (400 nm, violet) and 7×10^{-7} m (700 nm, red), or equivalently with *frequency* between about 8×10^{14} Hz and 4×10^{14} Hz.

volt The *SI* unit of *electrostatic potential*, *potential difference* or emf, represented by the symbol V. If an *electric charge* of one *coulomb* has its electrostatic potential increased by one volt, its *potential energy* increases by one *joule*, so that $1\,\mathrm{V} = 1\,\mathrm{J\,C^{-1}}$.

voltage Any quantity, such as *electrostatic potential*, *potential difference* or emf, that can be measured in *volts*.

watt The *SI* unit of power, or of the rate at which *energy* is transferred, represented by the symbol W. One watt is defined by $1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}}$.

wave A periodic disturbance that travels from one point to another. If the wave travels through a material medium, no *particle* in the medium is permanently displaced by passage of the wave. Waves may be *standing* or *travelling*. Some waves may be *transverse* or *longitudinal*. Transverse waves may be characterized by their *polarization*. Waves may also be characterized by their *frequency*, *wavelength* and direction of propagation.

wave number A quantity $k = 2\pi/\lambda$ that describes a *monochromatic wave*, where λ is the *wavelength* of the wave.

wavelength The spatial separation λ, measured along the direction of propagation, of successive points in a *wave* that differ in *phase* by 2π at any fixed time t. More crudely, the distance between successive peaks of the wave.

weak interaction A very short-range *force* that is responsible (among other things) for *beta decay*.

white dwarf star A compact stellar object with a *mass* similar to that of the Sun, which, following a fuel shortage, has collapsed to a size similar to that of the Earth. Consequently the average *density* of the object is very high, roughly a million times that of the Sun.

work If a constant *force* $\mathbf{F}$ acts on a *particle* as it moves through a *displacement* $\mathbf{s}$, the work done by the force on the particle is $\mathbf{F} \cdot \mathbf{s}$. For a *conservative force* the work done depends only on the initial and final positions of the particle.

X-rays *Electromagnetic radiation* with *wavelength* between 1×10^{-8} m and 1×10^{-11} m, or equivalently *frequency* between about 3×10^{16} Hz and 3×10^{19} Hz.

zero of potential energy A point at which the *potential energy* of a *particle* is set equal to zero.

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